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Verification of Monte Carlo transport codes against measured small angle p-, d-, and t-emission in carbon fragmentation at 600 MeV/nucleon

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Momentum spectra of hydrogen isotopes have been measured at $3.5°$ from ^{12}C fragmentation on a Be target. Momentum spectra cover both the region of fragmentation maximum and the cumulative region. Differential cross sections span five orders of magnitude. The data are compared to predictions of four Monte Carlo codes: QMD, LAQGSM, BC, and INCL++. There are large differences between the data and predictions of some models in the high momentum region. The INCL++ code gives the best and almost perfect description of the data.

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Contents

1. Introduction

The study of nucleus-nucleus interactions is one of the main aims of modern nuclear physics. During the last few years, apart from an investigation of fundamental properties of these interactions, special attention has been paid to precise phenomenological descriptions of the processes used in applications such as heavy ion therapy, radiation shielding, and radioactive ion beam design. Along the way a few simulation programs for nucleus-nucleus interactions have been created. They demand an experimental verification as well as refinement of their basic approaches. One of the aims of the FRAGM experiment performed at the TWA (Tera Watt Accumulator) heavy ion facility at ITEP was to obtain high precision data on nuclear fragmentation in the energy range accessible at this accelerator. In the framework of this experiment, the data has been taken for carbon ion fragmentation on a Beryllium target both in a wide incident energy range from 0.2 to 3.2 GeV/nucleon and in a wide energy range of the fragments from hydrogen isotopes to isotopes of the projectile nucleus. The measurements were performed in the projectile fragmentation region, i.e. in the so-called inverse kinematics. This method has substantial advantages over measurements in the target fragmentation region. At first, for the fragments moving in the forward direction, a relativistic boost provides larger acceptance in the projectile rest frame in case of an equal acceptance in the laboratory frame. Secondly, in inverse kinematics, there are no problems with a detection of fragments that are at rest in a projectile rest frame, because they are moving in a laboratory frame with a speed of the projectile nucleus. Yields of cumulative (high energy) protons were analyzed [1] in a framework of a multiquark cluster model and compared to a few models of ion-ion interactions in [2]. In this publication we give preliminary results on heavier hydrogen isotope emissions at 600 MeV incident carbon ion energy and compare them with the predictions of four Monte Carlo codes.

2. Experiment

The experiment was carried out at the TWA heavy-ion complex at ITEP which includes an ion laser source, a linac, a booster, and an accelerator-accumulator ring. Ions of 200-1000 MeV/A could be accumulated in this ring for successive use in experiments on high-energy-density physics or accelerated to a maximal energy of 4 GeV/nucleon. During our measurements, each four seconds the carbon ions C^{+4} were accelerated in the booster up to 300 MeV/nucleon. Then, while injection to the accelerator-accumulator ring they were totally stripped, captured in the ring and accelerated up to 600 MeV/nucleon. After that the beam was steered to the internal target of 50 μm Be foil strip providing the spill. It made simultaneously possible to have both a high luminosity because of multiple passage of the ions through the target and a small size of the source needed for a high momentum resolution of the subsequent magnetic analysis. The products of the carbon nucleus fragmentation outgoing at $3.5°$ were captured by the double-focus beam line (42 meters long). Sets of few a scintillation counters were placed at intermediate and final focuses for multiple measurements of dE/dx and time of flight (TOF). Fragments with different charge and mass were unambiguously selected on two-dimensional plots dE/dx vs TOF. The set up has been described in more detail in [1]. The fragment momentum spectra were obtained by beam line energy scan in steps of 50-200 MeV/c and fragments were selected using the procedure mentioned above. As a monitor, we used a telescope of three scintillation counters that viewed the target at $2°$.

3. Models

Recently, intermediate-energy ions have been used in various fields of nuclear physics and applications. This supports the demand both for deepening our knowledge of fundamental properties of ion-ion interactions and for developing methods of precise simulation of these processes on up-to-date levels. Both ways need large amount of various experimental data for testing new theoretical ideas and application programs. Here we use new data of the FRAGM experiment for verification of four "event-generators" widely used transport codes. They are LAQGSM03.03 [3], QMD [4], BC [5] and INCL++ [6]. LAQGSM03.03 (Los Alamos version of the Quark Gluon String Model) is supported and updated by LANL in the USA. It is a main part of the MCNP6 transport code [7]. The other three codes, QMD (Quantum Molecular Dynamics), BC (Binary Cascade), and INCL++(C++ (5.1.14) version of the Liege Intranuclear Cascade model) are free access programs from the GEANT4 package [8] supported by CERN. We used the version Geant4 10.0 (released 6 December 2013). In general, all of these codes consider ion-ion interactions as a sequence of the same processes such as intranuclear cascade, formation of excited prefragments and their successive deexcitation by evaporation (preceded by preequilibrium emission, in the case of LAQGSM03.03), Fermi breakup, and fission. But, an actual realization of these steps are different in different models. A description of these differences are far beyond the scope of this publication. Short and useful information on this subject can be found in the GEANT4 Physics Reference manual [8] and in Ref. [3] (for LAQGSM03.03).

4. Comparison of model predictions with experimental data

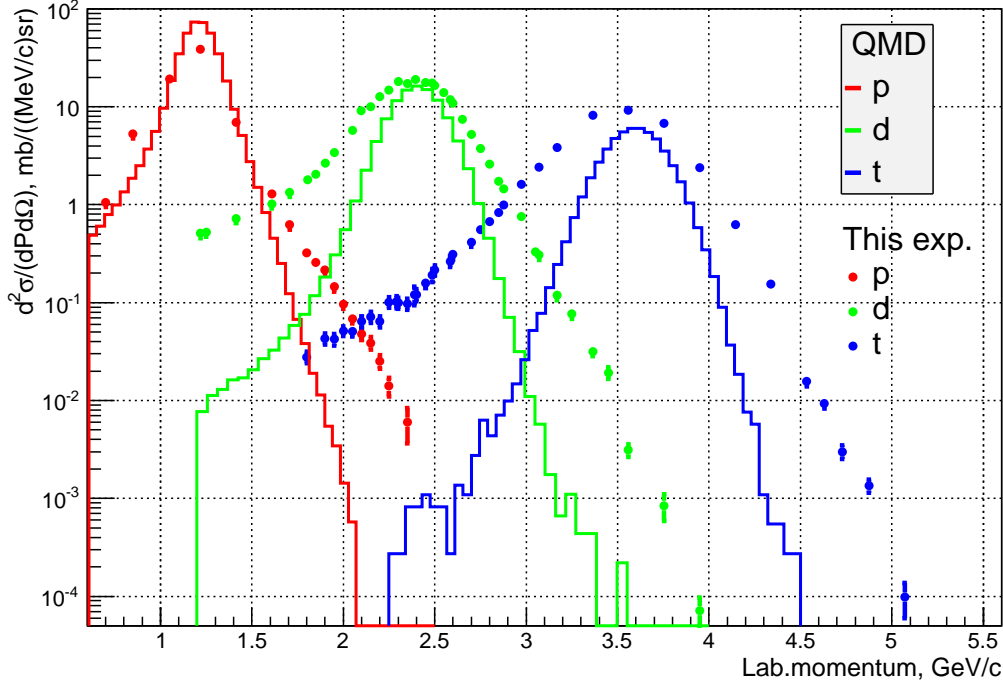Differential cross sections $d^2\sigma/dpd\Omega$ in a laboratory frame for proton, deuteron and triton

Figure 1: Laboratory momentum spectra of protons (full red circles at the left), deuterons (full green circles at the center), and tritons (full blue circles at the right) emitted at the $3.5°$ from fragmentation of 600 MeV/nucleon carbon ions on Be target in comparison with the predictions of the QMD model (red, green, and blue histograms, correspondingly).

yields at an angle of $3.5°$ and results of the simulations, using the models mentioned above, are given in Fig. 1 — 4 in logarithmic scale as a function of laboratory momentum of fragments. For normalization of calculations, the total inelastic cross section of $^{12}C + {}^{9}Be$ interactions equal to 823.8 mb was used in accordance with the LAQGSM03.03 prescription. The data of the FRAGM experiment were normalized to the BC predictions at the fragmentation peak maximum for protons. The BC was chosen because the shape of the fragmentation peak is in good agreement with that observed in the experiment. It can be seen from Fig. 4 that this normalization is of the same quality for the INCL++ model. For each fragment the spectrum demonstrates the so called fragmentation peak with maximum at the fragment velocity approximately equal to that of the projectile carbon ion. For protons the peak maximum is at $\sim$1.2 GeV/c, for deuterons – at $\sim$2.4 GeV/c, and for tritons – at $\sim$3.6 GeV/c. The experimental points go down at higher momentum (in the so called cumulative region) by 5 orders of differential cross section magnitude and show a less steep fall to lower momentum (midrapidity) region. As expected, all models give a reasonable qualitative description of the data. But there are substantial quantitative differences between the data and model predictions as well as between the different models.

The QMD model (see Fig. 1) gives good predictions for differential cross sections at fragmentation maxima, but the widths of the peaks for all fragments are too narrow. To give quantitative
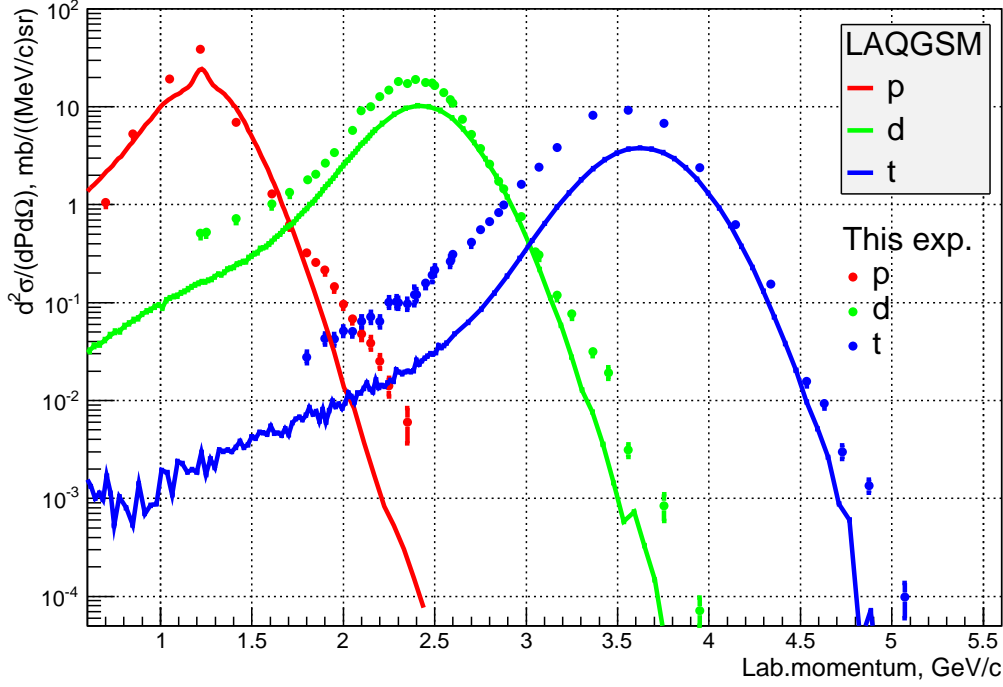
Figure 2: The same experimental data as in Fig.1 but in comparison with the predictions of the LAQGS03.03 model.

results we fitted these peaks of longitudinal momentum distributions with gaussians near their maxima in the projectile rest frame. For this experiment the r.m.s of the peaks are 72±5, 134±3, and 160±4 MeV/c for protons, deuterons, and tritons, respectively. While for QMD, these values are 56, 88, and 100 MeV/c. Here and later the errors for model calculations will not be given because they always can be made much smaller than experimental ones. The data of our experiment are in reasonable agreement with existing measurement [9] 63±4, 113±11, and 162±14 MeV/c. The narrow widths of the fragmentation peaks predicted by QMD result partly in a large underestimation of the differential cross section in the cumulative and midrapidity regions. The differences exceed two orders of magnitude at the edges of studied momentum intervals. For LAQGSM03.03 (see Fig. 2), the widths of the fragmentation peaks for deuterons and tritons are in reasonable agreement with the data. They are 147 and 159 MeV/c in projectile rest frame, respectively. For protons the predicted shape of the peak is not gaussian. Unfortunately the momentum step of our data are too large to check this prediction. LAQGSM03.03 underestimates the differential cross section at the fragmentation peak maxima by a factor of 2 and does not reproduce the cumulative tail of proton spectra at the 2.0-2.5 GeV/c laboratory momentum region, but shapes of deuteron and triton momentum spectra in the midrapidity region are reproduced well.

The BC model (see Fig. 3) gives slightly smaller values for fragmentation peak widths than LAQGSM03.03. The r.m.s. valuers are 62, 122, and 140 MeV/c for protons, deuterons, and tritons in projectile rest frame. The BC underestimates differential cross sections in the cumulative and
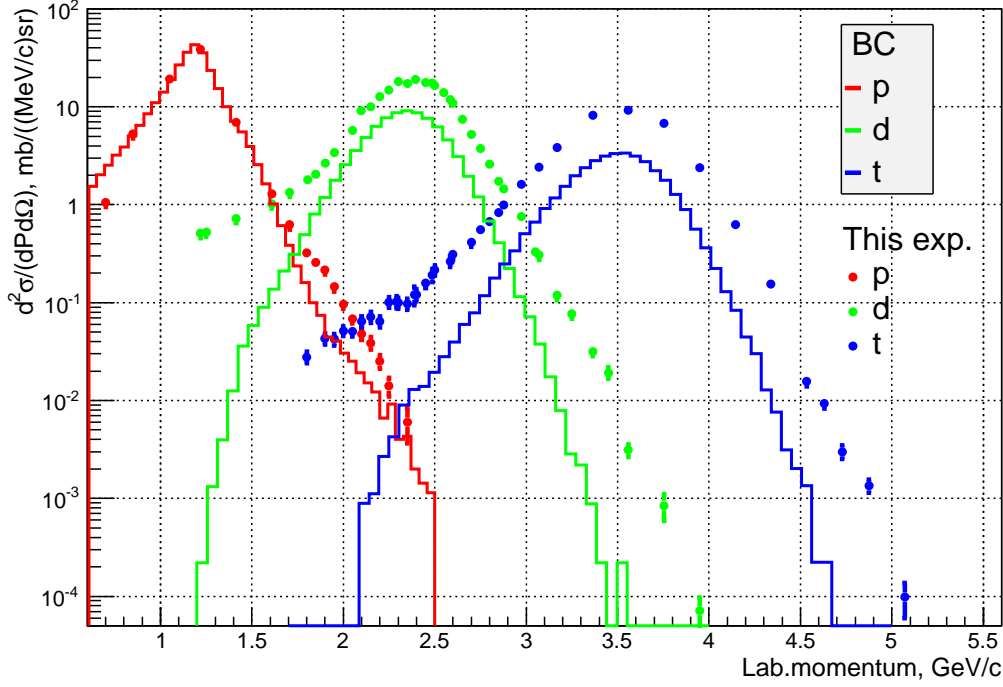
Figure 3: The same experimental data as in Fig.1 but in comparison with the predictions of the BC model.

midrapidity regions for deuterons and tritons, but gives reasonable description of the proton cumulative tail. Fig. 4 with the results of calculations by the INCL++ model demonstrates almost ideal agreement with the data of our experiment. The r.m.s. of the fragmentation peaks in projectile rest frame equal to 66, 140, and 167 MeV/c (for protons, deuterons, and tritons) are very close to our measurements. The proton spectrum is reproduced with high precision even in the cumulative region. The midrapidity region is also well described. The differential cross sections in the cumulative regions for deuterons and tritons are even slightly overestimated while all other models underestimate them in varying degrees.

5. Conclusion

The comparison performed shows a large potential of modern transport codes to describe new high precision data on fragmentation in ion-ion interactions. Apart from the QMD model, all other tested models (LAQGSM03.03, BC, and INCL++) give reasonable descriptions of proton, deuteron, and triton momentum spectra at 3.5° from 600 MeV/nucleon carbon fragmentation on Be targets. Some problems arise for the cumulative region where BC and LAQGSM03.03 substantially underestimate the differential cross section. In an absence of a recognized theory of cumulative particle production, the phenomenological mechanism of excited prefragment productions and their subsequent Fermi breakup is widely used in the transport codes. Good agreement between the data and predictions of the INCL++ model shows that this approach is very successful
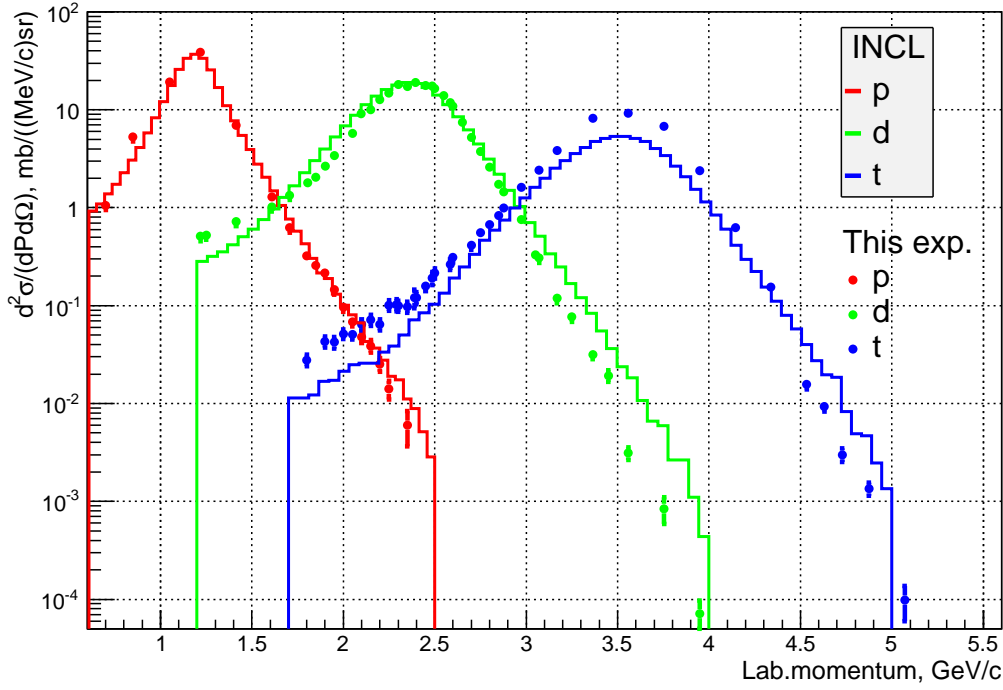
Figure 4: The same experimental data as in Fig.1 but in comparison with the predictions of the INCL++ model.

for a phenomenological description of the data of our experiment on cumulative proton, deuteron, and triton emission in carbon fragmentation.

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